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Max Gröbly

AN INVESTIGATION OF CUTTING SPEEDS
FOR ECONOMICAL PRODUCTION IN
METAL CUTTING INDUSTRIES

A THESIS

Presented to
the Faculty of the Graduate Division

by

Max Gröbly


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of the Requirements for the Degree
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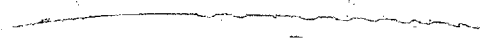
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June 1953

AN INVESTIGATION OF CUTTING SPEEDS FOR ECONOMICAL
PRODUCTION IN METAL CUTTING INDUSTRIES

Approved:







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ABSTRACT

AN INVESTIGATION OF CUTTING SPEEDS FOR ECONOMICAL
PRODUCTION IN METAL CUTTING INDUSTRIES
(66)

MAX GRÜBLY

Metal cutting is still an art; however, in spite of the increasing complexities brought about through new metals and alloys used in industry, considerable effort is being made to explain its mechanics theoretically. Despite this interest, only a few articles have dealt with economical considerations. In this respect, the cutting speed (the relative speed between the work machined and the tool) which results in the most economical production is the chief interest.

The purpose of this study is to investigate cutting speeds in order to determine the most economical production possible in metal cutting industry. In this thesis, the use of single point tools only is considered. Unfortunately, experiments involving them were not possible within the scope of this study, although such research would be very desirable.

In the first two chapters the more important facts in machining and their causes are briefly explained. Particular weight is given the discussion of the properties

of material cut and the tools. The recently developed cooling and lubricating of the tool point with "Hi-Jet" of the Gulf Oil Company is considered especially as an important development. The functions of chip breakers as a means of cutting into short or curled chips and of partial discharging of the load from the cutting edge are examined.

In the following chapters the cost factors involved in machining are discussed in detail and the formulas for cutting cost and the speed for economical production are derived. Examples are calculated and presented in graphs which are discussed.

Although the direct results are limited, some general recommendations are obtained. The use of carbide tools always results in lower machining costs and higher production rates, as long as the machining process is in control, or in other words, the failure of the tool is only caused by normal wear. The failure by breaking of the tool point is especially critical for intermittent cuts.

The cutting speed for economical production decreases with increasing handling cost, tool cost and grinding cost per tool sharpening. Increasing machine cost calls for higher cutting speed.

The machining cost for maximum production is, for cutting with high speed steel, only slightly larger than

the cost for economical machining. In machining with carbide tools the cost for maximum production is considerably increased. It is therefore recommended that between the limits of the speed for economical production and the speed for maximum production, a cutting speed which provides a higher production rate but which does not approach the cost for maximum production should be chosen.

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AN INVESTIGATION OF CUTTING SPEEDS FOR ECONOMICAL PRODUCTION IN METAL CUTTING INDUSTRIES

CHAPTER I

INTRODUCTION

General Considerations.--The most common operation in the metal working industry is the cutting of metal. This is done on a lathe, a boring mill, a milling machine, a drill press, a planer, a shaper, etc. Despite the importance of the cutting operation in industry, the problem of performing it economically cannot be solved by a simple formula.

Although many articles have treated the technical side of metal cutting, few are concerned with the economical aspects of tooling.

Until the end of the nineteenth century, the metal cutting process was seen as an art, which was bequeathed from father to son like so many other branches of the craftsmanship of that time. In 1880 Frederick W. Taylor began to attack the problem of metal cutting scientifically. His research continued until 1906 when he presented his paper, "On the Art of Cutting Metals," before the American Society of Mechanical Engineers.¹ This thorough study defines all factors involved in metal machining. It is so complete that many of the recent publications follow the

pattern and recommendations of Taylor. This fundamental study brought about as a result the use of the newly invented high speed steel, a chromium vanadium alloy steel with excellent properties as a cutting steel.

Efficiency in Metal Cutting.--Before details of the problem of metal cutting are presented, it may be of interest to consider the principle of cutting a material. The metal is removed from the stock by means of a tool which produces a chip. Thereby the tool is in intimate contact with the metal. The old idea of splitting metal like wood is now believed to be inconsistent since tests show that the tool, as well as the body and the chip, stays under considerable pressure. The chip itself is sliding with enormous friction on the tool face. This is the cause of the cratering there. The tool is sliding with the cutting edge over the machined work, which is responsible for the wear land.

Besides these two types of tool forces, there are still two other factors which are of highest importance in the machining:

1. The actual cutting forces, which are needed to divide the structure of metal into two pieces. These forces have to overcome the cohesion forces of the metal molecules.
2. The deformation of the chip has two different parts. One is caused by the building of the chip through the shearing forces and the other by the pressure forces on the tool face in bending the chip.

The energy of machining is therefore used to meet the four factors which, taken together, perform the work:

1. Work for overcoming the internal cohesion forces.
2. Work for deformation of chip.
3. Work of friction at tool face.
4. Work of friction at cutting edge.

Of these four factors for the cutting operation, only the first is actually needed. The others are a by-product of the machining process. Estimations of the efficiency will show that only 20 to 30 per cent or less of the energy is needed for performing the actual cutting. When, for instance, in the manufacturing of gas or steam engines a big effort is made to increase that efficiency to 40 per cent, it is astonishing how little is undertaken to improve the process of metal machining, despite its large application and importance.

Scope.--Considering the work on a lathe, one finds that after a certain time a break-down will occur, when the tool has become dull and must be exchanged. A new tool has to be fixed before starting again with production. Meanwhile, the dull tool is sent back to the grinding department for re-sharpening. Afterward it is sent again to the lathe where it will replace another dull tool. Normally the production can be increased by using higher cutting speeds. But this increases also the wear on the tool or decreases the tool.

life. The question is now which cutting speed is the most economical with respect to production.

The investigation in this thesis is solely concerned with economics of tooling, and the technical aspects are only touched as far as it is necessary to develop the procedure. All the investigations and studies are made with the use of a single-point tool, the best example of which is the lathe. Different reasons led to this decision. The whole work has a much more specific background and it is possible to make some calculations. On the other hand, the most literature and also the most reliable data which could be used for the examples concern this type of metal cutting.

Perhaps it is thought that a numerical solution in the form of tables or graphs should be achieved. Unfortunately, it is impossible, because too many of the variables change with the experiments, the location, the materials and the facilities, and even with the time. So it was decided to present the general solution in the form of a formula and calculated graphs with different variables. The constants and the variables are chosen as far as possible out of research works and in accordance with general practice. Although it is not possible to use the results immediately for a specific case, it is possible to approach a qualitative solution or an interpolated value which will be sufficient for many practical uses.

Experiments.--In the scope of this thesis it is unfortunately impossible to include experiments, despite the great need for them. But the following reasons were decisive in eliminating the experimentation from the program:

1. Only the most careful experimentation will deliver any valuable results, because of the complexity of the problem and the difficulty of instrumentation.
2. These experiments were not possible in the time available because they would have required a long preparation and difficult changes on a test lathe.
3. The experiments need careful measurements of all factors involved.
4. Only a considerable sequence of experiments is valuable, when different data are held constant.
5. Besides the enormous necessary time (one or even more years), these experiments would be very costly.
6. Finally, such research work would exceed the scope of this thesis considerably.

Definitions.--Throughout this study, if nothing else is marked, the standard terminology of the American Standards Association relating to single-point tools for lathes, planers, shapers, turret lathes and boring mills will be used. (See ASA B 5.22 - 1950). The most complete handbook

in the field of machining with single point tools is The Manual on Cutting of Metals,² which defines very clearly all the expressions and contains many data used in this study.

For this thesis the term "machine" will be used for "machine tool", and "tool" for "cutting tool". Instead of the symbol "s" for cutting speed as occasionally found in the literature, "v" (ft./min) will be used because it is generally employed throughout the machine industry as the symbol for speed. Similarly, "n" will be used in place of "N" for revolutions per minute. ("n" also appears as the exponent in the equation of tool life, and care must be taken not to confuse the two.)

The shape of the tool tip is very important for the conditions on the cutting edge. So it seems advisable to show here a set of typical tool designations for one tool as it will be used in this paper. Figure 1 shows the tool designations 8,22,6,6,6,15,3/64. They may also be written 8,22,6(10),6(10),6,15,3/64, in which the value of (10) would indicate the clearance angle below the 6° relief angle. In the case that the relief and clearance angles are given as being normal to the cutting edges, then the tool designations may be written:

	8^{n}	14^{n}	6^{n}	6^{n}	20	15	1/8
Normal ^a back rake angle...	:	:	:	:	:	:	:
Normal ^b side rake angle.....	:	:	:	:	:	:	:
Normal ^a end relief angle.....	:	:	:	:	:	:	:
Normal ^b side relief angle.....	:	:	:	:	:	:	:
End cutting edge angle.....	:	:	:	:	:	:	:
Side cutting edge angle.....	:	:	:	:	:	:	:
Nose radius.....	:	:	:	:	:	:	:

a - Normal to end cutting edge

b - Normal to side cutting edge

Other symbols, as those for standard terms, are explained when they occur.

Basic formulas are found in any machinist's handbook.

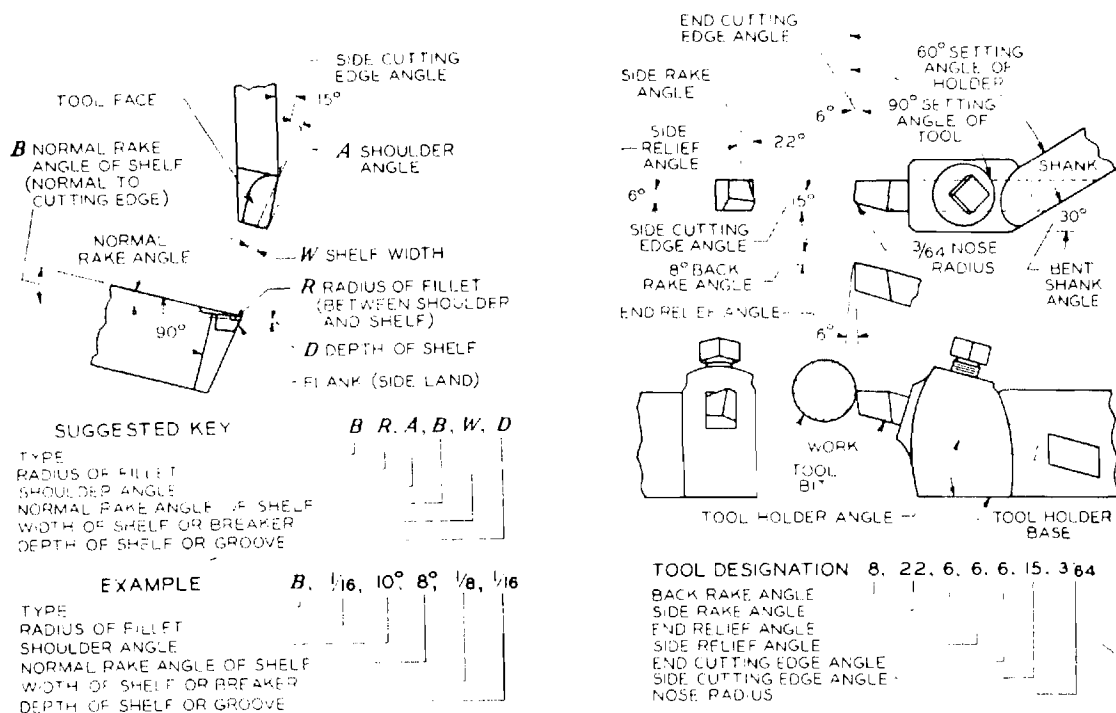


Figure 1. Tool Designation for a Typical Tool and Holder

CHAPTER II

FACTORS INVOLVED IN METAL CUTTING

In the machining process more factors are involved than would appear from the first view. First of all, the material cut and the material of the tool are of highest importance. The nature of both varies widely according to the heat treatment received. The shape of the tool, as well as feed and speed, will influence the machinability of the material. Other important factors in machining are the coolant used, the chip breaker, the stability of the machine, etc.

Usually the tool life is regarded as a measure of the cost of tools. In 1894 Frederick W. Taylor introduced as a standard of measurement a "twenty minute tool life", which was the cutting speed required to give a tool a life of twenty minutes. This method does not present a picture of how tool life varies with cutting speed. Subsequently, it became common practice to represent tool life in the form of a curve in which the logarithm of the cutting speed (sfpm) is plotted against the logarithm of the tool life in minutes. Accelerated tool life curves plotted in this way are linear and can be represented by the equation

$$v \cdot T^n = C$$

(1)

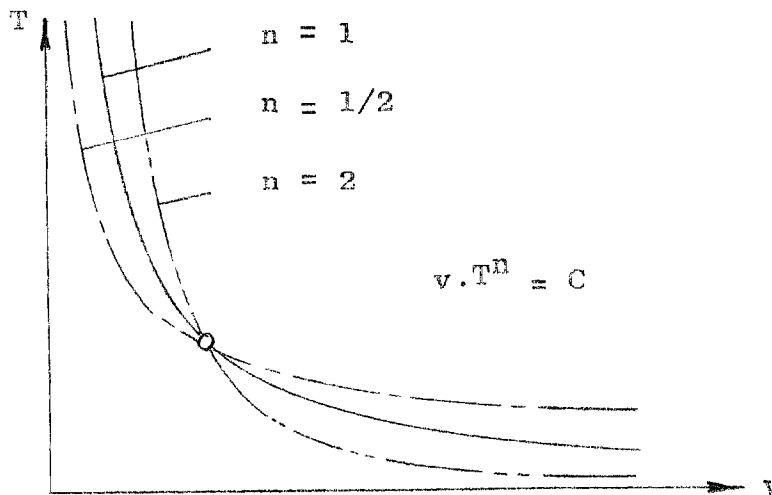


Figure 2. Shapes for Hyperbolic Curves with Different Exponent n

From Figure 2 one sees the principal course of such curves. In practice the values of n vary between 0.02 and 0.5. That means that if the tool use is plotted in the range where the slope of the curves is very steep, then our tool life expectancy is greater than one minute, or the speed is smaller than the value for C . Despite the fact that the above formula gives only an approximation to the real conditions, it is the only mathematical approach to the problem at present.

To get better acquainted with the complicated mechanism of cutting metals without going into details, it is necessary at least to summarize the most important facts of the main factors involved in the machining.

Machinability.--The machinability rating depends not only on the chemical compositions, toughness and hardness of the

material but also on its microstructure. For instance, two shipments of steel of exactly the same chemical composition, range and hardness can have marked difference in machinability, depending upon their difference in microstructure. Furthermore, the microstructure of a certain grade of steel that offers optimum machinability for one type of operation may offer difficulties for another.

Machinability generally includes a concept of tool life, surface finish and speed of cutting. Most jobs demand long tool life and high-speed cutting for economy, but at the same time many operations require smooth surface finish. Machinability therefore involves tool life, tool performance, surface finish, machine speed, feed and depth of cut, character and design of cutting tools, cutting fluid, and also the quality, composition, hardness and microstructure of the material. Each of these factors can be further subdivided as follows:

Material Cut

Composition

Grain size

Melting and casting process

Fabrication: cast, forged, drawn or rolled

Heat treatment: annealed, hardened, etc.

Properties: tensile strength, ductility and hardness

Size and shape

Microstructure

Cutting Tools

Alloy composition

Heat treatment

Hardness and strength

Design, form, shape, angles

Cutting Fluid

Water soluble, mineral, lard, or sulphurized oil
 Cooling properties
 Lubricating properties

Operating Machine

Type of machine
 Rigidity of tools and work holding device
 Feed
 Speed
 Depth of cut

This list is obtained from Materials and Methods and gives a very good overall picture of the broad field of machining. Some additional remarks may be helpful for better acquaintance with the complicated mechanism of cutting metals, although these remarks will not be very detailed.

Material.--The material is one object which takes active part in the machining process, so some comments on the properties of this very important factor seem advisable. Metals are here considered as ferrous or nonferrous. The nonferrous metals are, with very few exceptions, easy to machine. And normally the economical limits are given by the mechanical condition of the machines. Because there are not many problems in machining nonferrous metals, there does not exist an extensive literature for them as there is for the other group of metals.

The ferrous metals are still the most widely used material for machine shops. They can be grouped as cast iron, steel and alloy steel. With different content of alloying metals or carbon (carbon as such is not called an

alloying element), or with different heat treatment the machinability varies in a wide range. Up to the present time no general theory for the different steels has been advanced. The standardization of recent years has brought some uniformity in composition and properties of materials, but even so it is impossible to find an exact relation between machinability and the condition of the steel. Therefore, it is necessary to investigate the machinability for each separate case, despite the general rule that the machining is more difficult with increasing hardness of the material cut. On the other hand, the phase, the structure and the impurity of the material are very important. Alloying elements such as sulphur, phosphorus, and lead improve the machinability as does extruded graphite for cast iron.

In summary, it can be seen that the material can have nearly infinitely different forms, and the characteristics cannot be predicted. Furthermore, despite the general rule of the dependability of the machinability as a function of the hardness, the necessary data can only be obtained by experiments in laboratories for each single case.

Tool Material.---Satisfactory tool material must possess several characteristics:

1. Hot Hardness. At the operating temperature the hardness of the tool must be appreciably greater than that of the metal cut. This item becomes increasingly important as the speed of the cutting

operation is raised and the high-temperature strength of the metals becomes greater.

2. **Wear Resistance.** Welding and strain-hardening characteristics of the tool relative to those of the metal cut must be such that excessive wear does not occur in the operating range of speed.

3. **Toughness.** The tool must not be so hard that it is brittle and weak in tension. This is particularly important in connection with interrupted cuts.

4. **Low Friction.** The coefficient of friction between chip and tool should be as low as possible in the operation range of speed and feed, for least tool wear and best surface finish.

5. **Favorable Cost.** Increased cost of new tool material and its fabrication must be more than offset by the savings from increased production, and tool life, decreased labor and overhead.

There is no single tool material that is best in all the above respects. Relative importance of each item will change with the nature of the product (high or low precision or cost), volume of production, type of machining operation (intermittent or continuous cut, roughing or finishing, high or low speed, etc.), tool design details, general condition of the machine tool and physical characteristics of the work material.

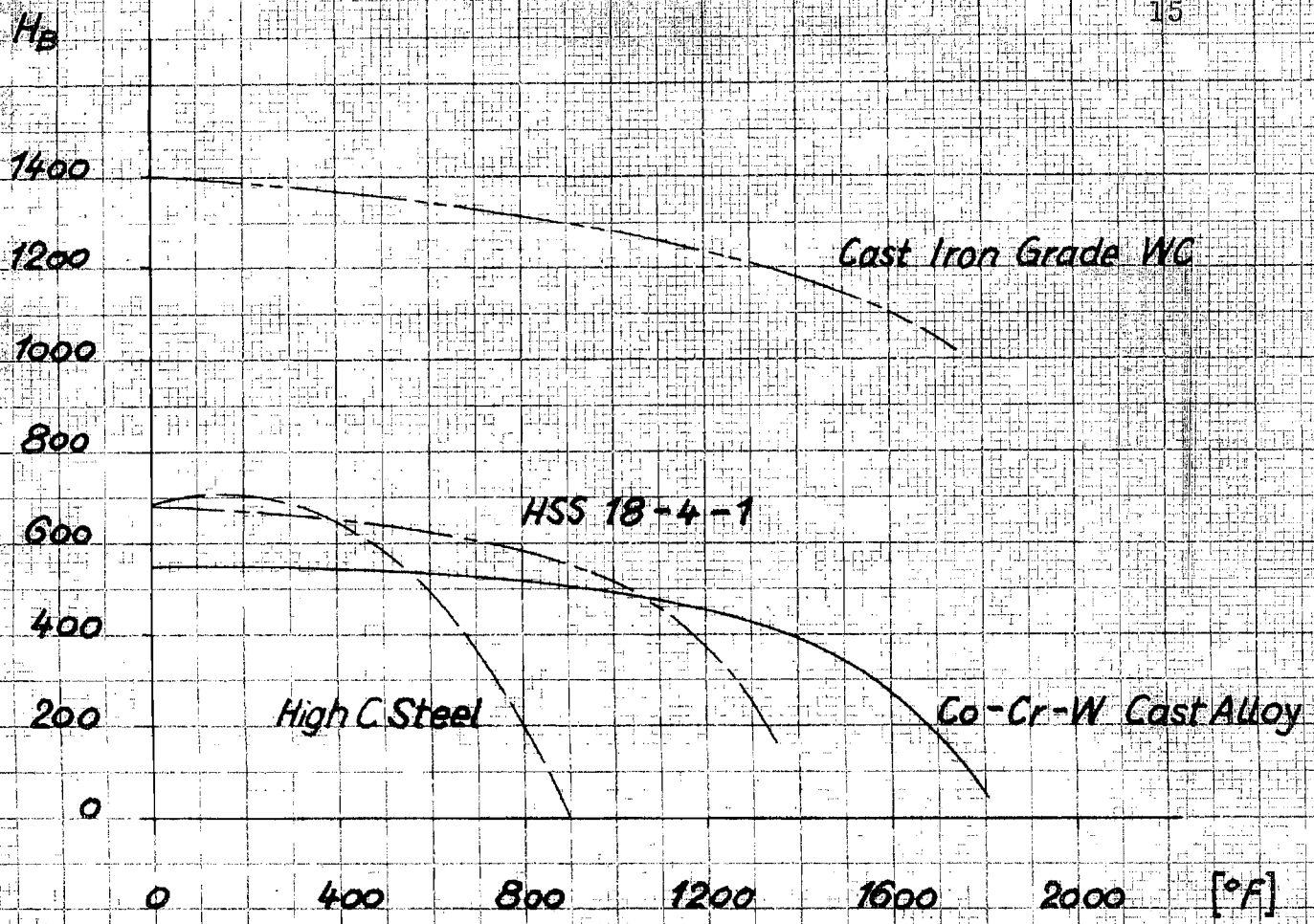


Figure 3. Hot Hardness of Different Tool Materials. Hot hardness, a necessary property of cutting-tool materials, depends on type of materials and alloying constituents. Note how Cobalt improves hot hardness.

Today five different types of tools are commonly used:

1. Straight carbon tool
2. Alloy tools
3. HSS-tools (high speed steel tools)
4. Carbide tools
5. Diamond tools

Carbon Tool Steel

The carbon tool steels have low hot hardness and a poor hardenability. They are limited to tools of small section which operate at relatively low speed. Their nature is more or less the same as that of machined steel, which is the cause for the poor cutting characteristics. The manner in which Brinell hardness of hardened carbon-steel tool decreases with decreased temperature is shown in Figure 3. (From the article of Milton C. Shaw and Prescott A. Smith.⁴) This fact and the low cost of other tool material have brought it about that the straight carbon tools are today no more in use.

Medium Alloy Tools

These steels are alloys with small amounts of alloying components as tungsten, manganese, chromium, molybdenum, etc. These additional components improve the wear resistance but not the hot hardness. Therefore, this type of tool is used for reamers and taps. The costs are approximately the same as for HSS tools which fact is the reason for the small use of this type.

1. The cast-iron grade, consisting of tungsten carbides with cobalt as a binder, for machining cast-iron and nonferrous metals.
2. The steel grade, consisting of tungsten, titanium and tantalum carbides with cobalt binder, for machining steels.

Composition of cemented carbide is not the sole item that determines its physical properties. The mean grain size is also important. While the only difference between the 44A and 883 grades is the grain size, the coarser-grained material is softer and more shock resistant.

The cemented carbides are unusual in several respects:

1. They have high hardness over a wide range of temperature.
2. They are very stiff (Their Young's modulus is nearly three times that of steel).
3. They exhibit no plastic flow (yield point) when under stresses as high as 500,000 psi.
4. They have low thermal expansion compared with steel.
5. They have relatively high thermal conductivity (especially the cast-iron grades).
6. They have a strong tendency to form pressure welds at the low cutting speeds.

These unusual properties call for special considerations in the design and use of carbide-tipped tools. The great stiffness of carbides requires that they be well supported on

a shank of sufficient thickness, because even a small amount of bending deformation may induce very high tensile stresses.

Like all brittle materials, cemented carbides are weaker in tension than in compression. A cemented carbide tool should be proportioned so that tensile stresses are kept low. This is particularly important when the tensile stresses arise from dynamic or shock load, as intermittent cutting.

The relatively small coefficient of expansion of cemented carbides makes it necessary to use a relatively thin layer of braze metal. If this precaution is observed, the braze will not crack upon cooling as a result of large tensile stresses arising from different contractions of the carbide tip and the braze metal.

Diamond Tools

Diamond tipped tools are used for special applications, such as the production of surfaces of high finish on soft materials that are normally difficult to machine. The general properties of diamond may be summarized:

1. Hardest known substance (Brinell hardness, 7000)
2. Lowest thermal expansion of any known substance (about 60 per cent that for invar and about 12 per cent that for steel).
4. Poor electrical conductivity.
5. Burns to CO_2 when heated to about 1500°F in air.
6. Very low coefficient of friction against metals.

The high cost of diamond tools and the high brittleness limit the use of the diamond as a tool.

Tool Shape.--The tool shape is to a certain extent related to the properties of the material cut. It controls the flow of the chip and the roughness of the surface cut. The shape is definitely very important for power consumption of the machine. Normally the tendency is toward increasing the positive cutting angles. But here exists a practical limit established by the tensile strength of the tool material. Big positive cutting edge angles tend to chatter. Negative angles of the cutting edges are proposed for brittle tool materials as cemented carbides, in connection with high cutting speeds. But here the power consumption is several times as high as with normal cutting angles. Normally the experimenters have used one specific tool designation throughout their experiments, so a definite relation between the tool shape and the tool life has not been established.

Coolant.--A very important factor in machining is the cooling of the cutting edge. The coolants should accomplish the following purposes, singly or in combination:

1. To keep the tool cool and prevent its being heated to a temperature at which its heat hardness and resistance to abrasion are reduced.

2. To keep the work cool, thus preventing its being machined in a warped shape resulting in inaccurate final dimensions.
3. To reduce the power consumption, wear on tool and the generation of heat by lubrication.
4. To provide a good finish on the work.
5. To aid in providing a satisfactory chip formation.
6. To wash away the chips, particularly in deep hole drilling, hacksawing, milling and grinding.
7. To prevent corrosion of the work and the machine.
8. To lubricate moving machine parts close to the cutting edge.

The cutting fluids may be divided into the following classes:

1. Air, used as a blast or induced draft, or without artificial draft.
2. Aqueous solutions, such as plain water or water containing a small percentage of alkali.
3. Emulsions of a soluble oil or paste.
4. Oils of animal, vegetable, fish, or mineral types, which may be used straight, compounded, or blended.
5. In recent years solid CO_2 has been used as a coolant.

Because of the great latent heat the cooling of the tool tip is excellent, but CO_2 does not lubricate, so its use is very limited.

In the last two years the Gulf Oil Company investigated the possibility of sending a high pressure oil stream from behind between the metal out and the clearance face.⁵ The results of the test seem to be exceptionally good. Some published data of this new method of cooling and lubricating will be used for the calculations of examples.⁶ The principle of the method involves the oil jets reaching directly to the hottest point on the tool point. The oil, in evaporating, cools the tool and even a small percentage is able to reach the tool face where it lubricates the high pressure motion between chip and tool face. The result of this high pressure lubrication is a considerably longer tool life or a higher cutting speed.

Chip Breaker.--Chip breakers have two different purposes:

1. As the name indicates, their purpose is to break the chip so that it can be easily removed from the work and handled.
2. If they are applied in the proper way, the load of the tool tip is distributed to the chip breaker which is distant from the critical tool tip.

On the other hand, a chip breaker requires increased power of from 5 to 15 per cent.⁷

CHAPTER III

COST OF MACHINING

The production cost of a metal cutting operation may be broken down into four parts:

1. The cutting cost,
2. The cost of the tool,
3. The cost of grinding,
4. The cost of handling the tool.

These four factors and their sum, the total cost per piece machined, are the subject of this thesis and will now be discussed. In the preceding pages the technical difficulties were explained in order to show the complexity of metal cutting. However, the study will now emphasize the economical factors in tool maintenance with the assumption that the best possible technical concept for the experiments is used.

The cutting speed (v) has in the study of costs a particularly important role. It determines, when all the other factors are held constant, the power consumed, the time for machining the piece, and the life of the tool until this is subjected to a fixed wear. So it is obvious that the cutting speed should be taken as a variable and the equation for the cutting cost expressed as a function of v .

Machine Rate

The cutting cost itself is composed of the machine rate and the time during which the machine is occupied with the operation. The rate of the machine cost consists of a constant and a variable member, if we take the cutting speed as the independent variable.

Fixed Machine Rate.---This is given by the original machine cost, the depreciation rate, the taxes and insurance, the maintenance and repair cost, the latter four being normally figured as yearly rates. The labor cost, including workmen's compensation and insurance, comes in the figure as hourly costs.

Table 1 shows this computation for machine cost varying from \$5,000 to \$20,000. The depreciation is calculated with capital recovery for 6 per cent interest and twenty-year depreciation.⁸ These values are used because they are in general use in American industry.

The percentages for taxes and insurance, as well as for maintenance and repairs, are estimates of the average values used in industry. This is also true of the labor cost.

The machine rate determines to a great extent the actual cost, but if one is interested only in the speed connected with minimum cost, the machine rate is rather unimportant. From the theoretical standpoint, all the

overhead cost should be included in the machine rate, but it would be hard to find a limit for the overhead figure, and a safety factor would also have to be included. However, the omission of this overhead cost will not change the results in any way, for this cost can be accounted for by multiplying the results by a special factor.

Variable Machine Rate.---Under the fixed machine rate, power consumption was purposely neglected. It is a direct function of the cutting speed. Although its exact function is not known, it is still possible to assume, without a large error, a linear function.

In Figure 4 the forces on the cutting edge are shown. From these it is possible to calculate the power used on the tool tip.

Power on tool tip

$$P_{\text{Tip}} = F_T \cdot v + F_L \cdot f + F_R \cdot f_R \quad (2)$$

This equation expressed in kw transforms to

$$P_{\text{Tip}} = \frac{F_T \cdot v}{24200} + \frac{F_L \cdot f \cdot n}{12 \cdot 24200} + \frac{F_R \cdot f_R \cdot n}{12 \cdot 24200}$$

Because the feed rate for longitudinal and radial speed are, compared with the speed v , very small the equation can be simplified by neglecting these two members of it.

$$P_{\text{Tip}} \simeq \frac{F_T \cdot v}{24200} \quad (3)$$

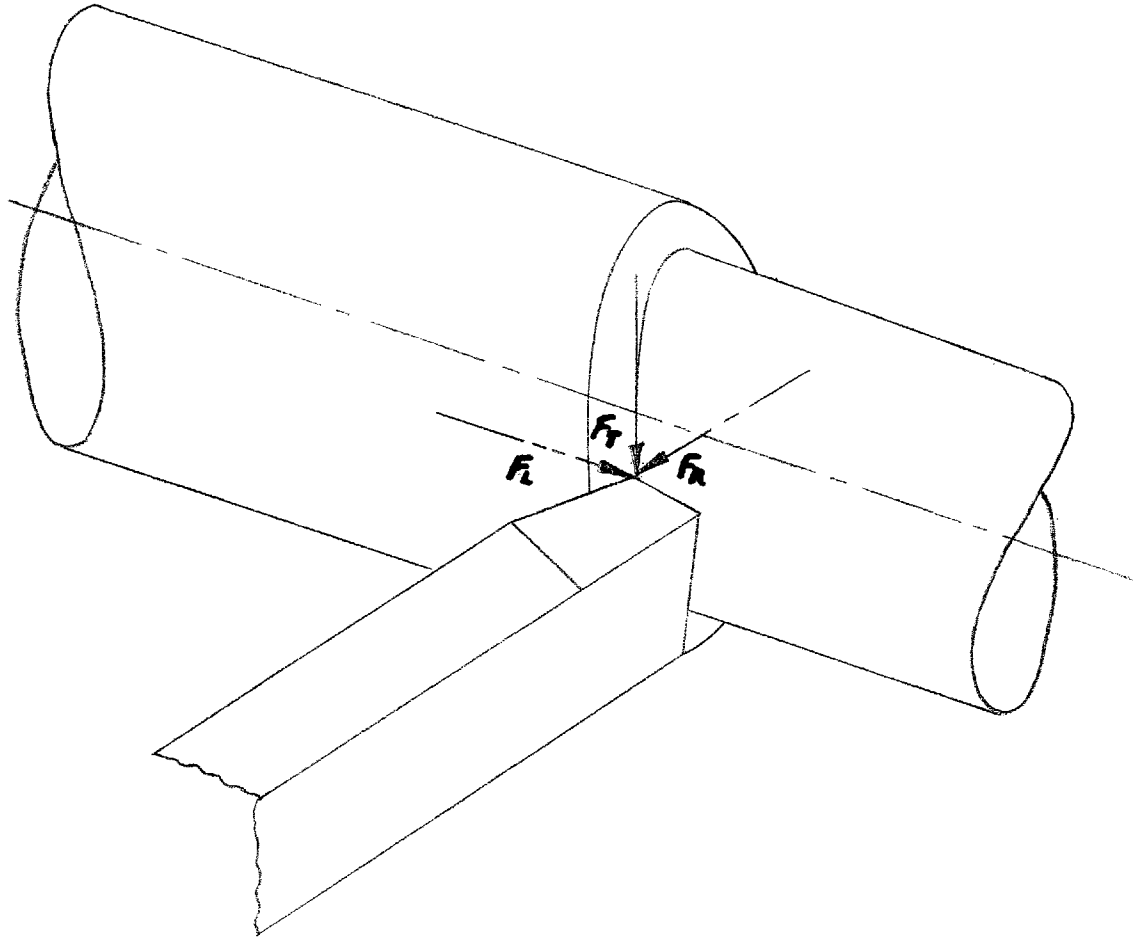


Figure 4. Forces Acting on the Work Piece

Out of practical experiments the cutting forces can be approximated by equations in function of the cutting depths and the feed. For an average tool signature we find the following values⁹

$$F_T = 120,000 \cdot f^{0,8} \cdot d \quad (4)$$

Hence, the formula for the power used is obtained directly. If an overall efficiency of the machine is estimated to 60 per cent and the cost per kwh = 0.015 \$/kwh, the formula reduces finally to

$$P_t (\$/min) = 9 \cdot 10^{-5} \cdot d \cdot f^{0,8} \cdot v \quad (5)$$

$$P_t (\$/min) = k \cdot v$$

In Table 2 the k-values for different feed (f) and cutting depth (d) are calculated. It is obvious that the k values are very small.

The sum of the fixed and the variable machine rate is equal the total machine rate:

$$M = m + k \cdot v \quad (6)$$

Because the values of k are very small, this member becomes effective only over a certain cutting speed. If we take a significance level of 2 per cent for the lowest fixed machine rate and the biggest feed along with a normal cutting depth, it is possible to determine the speed limit up to which v has no influence upon the machine rate.

$$\begin{aligned}
 f &= 0,012 \text{ in/rev} \quad d = 0,25 \text{ in} \quad \therefore k = 1,83 \cdot 10^{-6} \text{ \$/ft} \\
 vk &= v \cdot 1,83 \cdot 10^{-6} < 2.4,196 \cdot 10^{-4} \\
 v &< 450 \text{ ft.min}^{-1}
 \end{aligned}
 \tag{7}$$

Below a cutting speed of 450 ft.min^{-1} it is not necessary to consider the variable member of the machine rate.

Machining Time

The machining time is the time during which the machine is occupied with the operation; it includes as well the actual time for cutting as well as the time for running the machine back to the beginning position, the loading time, the idle time and the portion of the original setting time per piece.

Actual Machining Time.---The actual machining time depends on the material to be removed, the feed and speed, as well as the cutting depth, which has only secondary influence. The amount of the removed metal can be obtained by a commonly used formula which is accurate enough for all practical purposes:

$$V = \pi D.L. d = 12a.d \quad (\text{in}^3) \tag{8}$$

The volume V of cut material, divided by the necessary speed, feed and depth delivers the cutting time (T_m).

$$T_m = \frac{\pi D.L. d}{12.f.v} = \frac{a}{f.v} \quad (\text{min/piece}) \tag{9}$$

As is seen here, actual cutting time varies inversely as the speed.

Idle, Loading and Feeding Time.---The idle, loading and feeding time is generally not affected by the speed, since these are operations under control of the operator. On automatic machines this is accomplished by a mechanism which is not controlled by the spindle, or cutting speed. The idle and loading time represent the non-cutting time, which may account a considerable proportion of the total time. This may be reduced effectively by using better design of fixture, by automatic control, by pre-locating tools, as in turret lathe, and also by automatic work handling. Since the time of these tasks may occupy such a large percentage of the total machining time, it is important that all these factors be considered carefully. However, the choice of the cutting speed that should be used during the cutting time is not affected by any of these factors. In our equation the idle, loading and feeding time will enter as T_1 .

Tool Setting Time.---The time for setting tools can be considerably reduced, especially in more complicated machines with different tools. This loss of working capacity of the machine has to be charged to each separate piece of the lot. The setting time is not affected by the speed, but by the type of machine and the job which should be performed. The time per piece produced is equal to:

$$\frac{T_s}{N_1} \quad (\text{min/piece}) \quad (10)$$

where T_s is the total setting time and N_1 the lot size.

Tool Resetting Time.--This is the time needed to exchange a dull tool for a sharp one. This operation is strictly controlled by the skill of the operator, the type of tool and machine. It consists of two separate operations, the releasing of the dull tool and accurately fixing and setting the sharp tool. It is self-evident that a sharp tool for exchange must be at hand at the time the other gets dull. This requires a sufficient supply of sharpened tools.

The tool resetting time (T_R) itself is not a function of the cutting speed, but it varies very much with the type of the machine, etc., so that for examples used herein estimates within a range are used.

For our calculations it is desirable to have the time of the cost per piece, and it is therefore necessary to divide the times which are obtained per sharpening by the number of pieces machined per sharpening (N_S).

$$N_S = \frac{T}{T_m} \quad (12)$$

where T is the tool life in min. With (1) and (9) this equation reduces to

$$N_S = \frac{C^{1/n}}{v^{(1/n-1)}} \cdot \frac{f}{a} \quad (13)$$

N_S is a higher exponential function of the cutting speed, since the exponent n is smaller than 1.

Tool Cost

The cost of the tool depends entirely on the type of tool used, the size and to a certain extent the purpose and shape. For these calculations the cost per sharpening of the tool is needed. This is not easy to determine, and unfortunately there are evidently no records which could give some evidence. Furthermore, it depends on the type of failure of the tool. For a single point tool in continuous cutting, there are three causes of failure:

1. Abrasion or wear on the flank below the cutting edge.
2. Wearing a cup in the tool face back of the cutting edge which becomes steadily larger and finally causes the cutting edge to crumble.
3. Combined flank and face wear.

But besides the failure through abrasion there exists the failure through the breaking-off of a part of the cutting edge. This indicates that the tooling is no more in control and either through a change of the cutting angles, the cutting speed or the total set-up, it must be improved. As far as this thesis is concerned, tool wear is limited to normal abrasion and the end of the tool life is clearly defined. Unfortunately this is not the actual case for two reasons.

First, our given tool life equation is only an approximation of the real function, and second, it represents

only a statistical average. If the equation were identical to the lower control limits of the tool life distribution, it would be possible to predict that there would be no tool failure below this curve with some accuracy. So a point could be reached where the change of tools could be prescribed after a certain predetermined time. Until today the judgment as to whether a tool is still sharp or has become dull is very much left to the operator or to the quality change which may be identified only after a certain time.

HSS - High-Speed-Steel.--In this thesis only high-speed steel and cemented carbides are dealt with. The high-speed steels are most convenient in connection with a tool holder. A relatively small tool bar of HSS material is clamped into the holder, so that practically the whole tool bar can be used for cutting. This material-saving device is not expensive and the tool bits are very cheap. (See the catalog of Harry P. Leu, Inc., Orlando, Fla.¹⁰) For HSS tool material the use of "Rex Tool Bits for Tool Holder" is assumed with a cross section of $1/4 \text{ in}^2$ and 21 bits per lb. at \$1.10. This means a tool cost per bit of

$$\$0.0525$$

Furthermore, an average number of grindings per tool of $N_c = 100$ times is assumed. This number depends very much upon the kind of tool failure and the amount of material removed per grinding.

$$C_T = \frac{0.0525}{100} = 5.25 \cdot 10^{-4} \text{ \$/sharpening}$$

If it is desired to have the tool cost per piece machined, C_T must be divided by the number of pieces per sharpening: N_S . The cost of the tool is normally so small that it can be neglected.

Cemented Carbide Tools.--Cemented carbide tools are bought either as finished tools or only the tips, which are brazed on the rigid tool holder. Because the rebrazing costs are about the same as those of new tools this possibility is neglected in this study, and tool size of BR 12 is assumed. (Catalog of Wendt and Sonis No. 52.¹¹) The cost for such a tool is \$2.40. Or, if it is considered that an average number of sharpenings of $N_S = 100$, one obtains a cost of tool per sharpening of

$$C_T = 0.024 \text{ \$/sharpening}$$

For comparing the cost, all cost elements related to the production of one piece are needed. That means that the tool cost must be divided by the number of pieces machined per sharpening:

$$\frac{C_T}{N_S} \quad (11)$$

Grinding Cost

Since no literature exists which would give some evidence for the true costs of the grinding of tools, it has to be estimated. The idea is that if the grinding of

tools is standard and routine work, there must exist one average time for the grinding and therefore one cost per sharpening a tool. Naturally, this value has to be established for each shop and depends on the type of grinder, the number of tools ground per year, and the skill of the operator of the grinding machine. The cost for dressing the grinding wheel and the wear of the wheel itself should also be in such a consideration.

For this study estimates have been developed and are put together into Table 3.¹² All the rates are the same as assumed for the machine tools (Table 1). Out of the table the cost per minute is obtained. This has only to be multiplied by the average grinding time, which is also estimated and varied. The grinding cost per tool sharpening is therefore

$$G \cdot T_g$$

where G is the grinding cost per minute and T_g the time used per sharpening. Generally speaking, in the first approximation this cost is not a function of the cutting speed.

Handling of Tools

In consideration of the cost of machining, the handling of the tool has also to be involved. When even cheap labor brings the dull tools to the grinding department and the sharpened back to the machine, it very soon amounts

to several per cent of the total cost. This is especially severe, because it does not affect the constant cost of machining but is a function of the cutting speed. Thus, when the tool life is long or the cutting speed low, the sharpening happens only occasionally and the handling cost per piece produced is very small. But when the tools have to be sharpened after only a few minutes, the shop clerk is constantly occupied with carrying tools to the grinding department and back to the machine.

The estimated handling time T_h varies between four and twenty minutes at an estimated labor cost of \$0.75 per hour. The cost of handling the tool per sharpening is expressed by H.

CHAPTER IV

ECONOMICAL MACHINING

Total Cost of Machining.--The total cost of machining is the sum of the items discussed in Chapter III. All the costs are related to the production of one piece. The respective formula appears as follows:

$$C_m = M \left[(T_i + T_m) + \frac{T_s}{N_1} + \frac{T_r}{N_s} \right] + \frac{G \cdot T_g}{N_s} + \frac{C_T}{N_s} + \frac{H}{N_s} \quad (15)$$

M -- Total machine rate (\$/min)

G -- Grinding rate (\$/min)

C_T -- Cost of tool per sharpening (\$/sharpening)

H -- Cost of handling the tool per sharpening (\$/sharpening)

T -- Tool life (min)

T_i -- Idle, loading and feeding time (min/piece)

T_m -- Actual machining time (min/piece)

T_s -- Tool setting time (min/lot)

T_r -- Tool resetting time (min/sharpening)

T_g -- Tool grinding time (min/sharpening)

N₁ -- Lot size (number of pieces)

N_s -- Number of pieces cut per tool sharpening (piece/sharpening)

This formula may also be expressed in this form:

$$C_m = (m+k.v) \left\{ \left[T_i + \frac{T_s}{N_1} + T_r \cdot \frac{a}{f} \left(\frac{v}{C} \right)^{\frac{1}{n}} \right]^{\frac{1}{n}} \cdot v^{-1} \right\} + \frac{a}{f} \left(\frac{v}{C} \right)^{\frac{1}{n}} \cdot [G \cdot T_g + C_T + H] \quad (16)$$

If $v < 450 \text{ ft.min}^{-1}$

$$C_m = m \left[T_1 + \frac{a}{v \cdot f} + \frac{T_s}{N_1} \right] + \frac{a}{f} \left(\frac{v}{C} \right)^{\frac{1}{n}} \cdot v^{-1} \left[m \cdot T_r + G \cdot T_g + C_T \cdot H \right] \quad (17)$$

This equation represents a curve which is the superposition of a constant member $(T_1 + \frac{T_s}{N_1})$, a member which is reciprocally proportional to the speed $(\frac{m}{f})$ and the member which is an exponential function of the ratio v/C .

The constant members do not influence the shape of the curve as such, but change only the absolute value of the cost.

The member of the actual machining time has a hyperbolic shape, a high value for small cutting speed, with a sharp decrease in the beginning and with high cutting speed asymptote at the v -axe.

The last member has, because of the ratio v/C , no measurable value with low speed, but after the speed has reached a certain value the function increases very fast. The superposition results in a curve which has high values with low and high cutting speed and a distinguishable minimum. Here the objective is to find the speed which will result in the minimum cost, although this study is more concerned with the speed than with its cost.

The curve for the machining cost for the machine rate including the variable part $k \cdot v$ has approximately the same shape.

Conditions for Minimum Cost.--In many cases industry tries to work most economically with the given equipment. In all these instances it is important to work on the minimum point of the cutting-cost curve, when all the other variables are held constant. Mathematically this can be achieved by differentiating the cost equation to the cutting speed v , and setting it at zero. However, this new equation is only solvable for v when the machine rate is constant, or for values for v when $v < 450 \text{ ft.min}^{-1}$.

$$\frac{dC_m}{dv} = 0 = \frac{(-1)m.a}{v^2 \frac{1}{F}} + \left(\frac{1}{n} - 1\right) \frac{a}{F} \left(\frac{v}{C}\right)^{\frac{1}{n}} \cdot v^{-2} \left[m.T_r + G.T_g + C_T + H\right] \quad (18)$$

Solved for the cutting speed v , the equation becomes

$$v_e = \frac{C.m^n}{\left(\frac{1}{n} - 1\right)(m.T_r + G.T_g + C_T + H)} \quad (19)$$

By using the tool life definition we get the formula for the tool life for economical machining.

$$T_e = \left(\frac{1}{n} - 1\right) \frac{m.T_r + G.T_g + C_T + H}{m} \quad (20)$$

If $v > 450 \text{ ft.min}^{-1}$ one of the approximations consists in plotting the cost curve and looking for the minimum point. Another way would be to differentiate the cost equation, set it at zero, and solve it graphically. But this has the disadvantage that it is as tedious as plotting the cost curve and not much more accurate. Also, it does not deliver the actual cost.

Conditions for Maximum Production Rate.--If the cost is not important, which is often the case where the output is urgent or the costs can be set freely, then the economical factors in the machining are unimportant and the total time of the machining must be minimized. Mathematically the equation for machining time must be differentiated for the production time T_p to v .

$$T_p = T_i + \frac{T_s}{N_1} + T_m + \frac{T_r}{N_s} \quad (21)$$

With $N_s = \frac{T}{T_m}$ (11) and $T_m = \frac{a}{f \cdot v}$ (9)

$$T_p = T_i + \frac{T_s}{N_1} + \frac{a}{f \cdot v} + \frac{T_r}{C^{\frac{1}{n}}} \cdot \frac{a}{f} \cdot v^{\frac{1}{n} - 1} \quad (22)$$

$$\frac{dT_p}{dv} = 0 = 0 + 0 - \frac{a}{f \cdot v_p^2} + \frac{T_r}{C^{\frac{1}{n}}} \cdot \frac{a}{f} \left(\frac{1}{n} - 1 \right) v_p^{\frac{1}{n} - 2} \quad \text{or}$$

$$1 = \frac{T_r}{C^{\frac{1}{n}}} \left(\frac{1}{n} - 1 \right) v_p^{\frac{1}{n}} \quad \therefore$$

$$v_p = \frac{C}{\left(\frac{1}{n} - 1 \right) \cdot T_r^n} \quad (23)$$

It is important to note that the speed for maximum production is not at all affected by the variable member of the machine rate, and is only a function of the setting time T_r and the constants C and n .

Sometimes it may be interesting to know the ratio between the speed for maximum and economical production. For cutting speeds below 450 ft.min^{-1} the formula has the simple form

$$\frac{v_p}{v_e} = 1 + \left(\frac{G.T_g + C_T + H}{m.T_r} \right)^n \quad (24)$$

Values near one indicate that the economical cutting speed and the speed for maximum production are about the same. Furthermore, the formula indicates that the cost for grinding, handling and the wear of the tool is small compared with the cost for resetting the machine. That means, for instance, that for a very expensive machine and a relatively long resetting time the cutting speeds for highest economy and production are about the same.

CHAPTER V

DISCUSSION

The formulas developed in the previous chapter were employed on some specific examples, and the results plotted in graphs. The actual calculations are not presented here, and the original data for each example are collected in the Appendix.

Curves for Cutting Cost

The Elements of Cost.--In Figure 5 the elements of the cost and the total cost are plotted against the cutting speed v . For the example of cutting SAE 1045 with HSS-tool and cooling with overhead flooding, the money value of the idle time and the portion of the setting time per piece are constant, the line horizontal. The actual machining cost per piece is a declining, hyperbolical curve with gradually decreasing slope. In other words, when the machine is operated with low cutting speeds, the time required for producing one piece, or the equivalent cost, is large and decreases gradually with increasing cutting speed.

The cost for the resetting, regrinding, handling and the use of the tool per piece is practically zero, up to a certain cutting speed. In this range the tool life is so

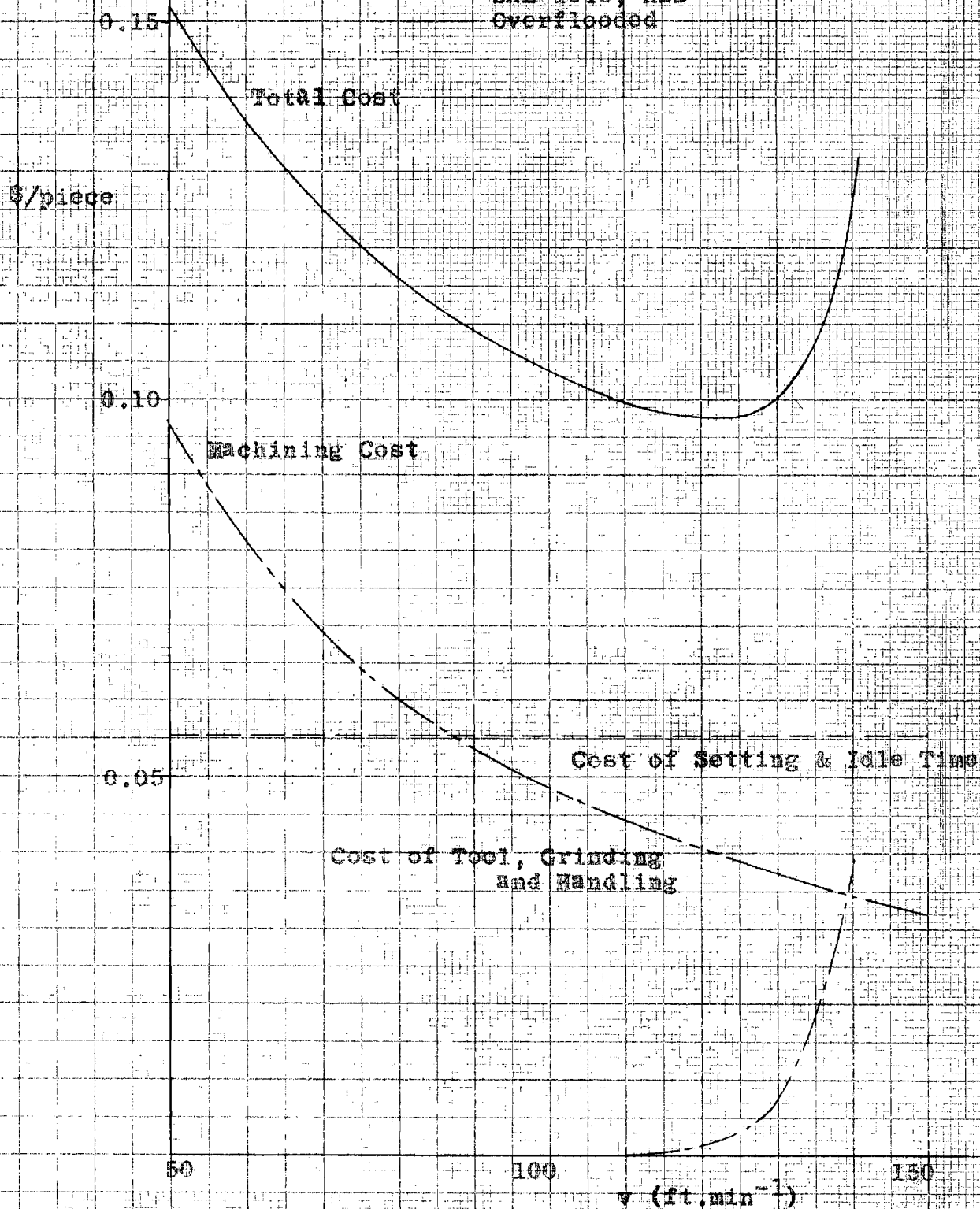
SAE 1045, HSS
Overflooded

Figure 5. Elements of Cutting Cost: Constant Cost, Actual Machining Cost and Cost for Re-sharpening the Tool.

long that the reconditioning of the tool occurs only occasionally (after one or more hours of production) and the respective costs are of minor importance. But after the cutting speed has passed its limit, this part of the cost increases, after the manner of an exponential curve, very rapidly.

The resultant of these components, or the total production cost per piece, first decreases in the same manner as the machining cost curve and after reaching the minimum it increases with the cost for tool maintenance. The minimum cost is obtained at the "economical" cutting speed $v_e = 122 \text{ ft.min}^{-1}$. The speed for maximum production is obtained as $v_p = 126 \text{ ft.min}^{-1}$. In this case the two speeds are nearly identical, which is a desirable situation.

Cost Curve with Variable Factor for Speed.---For higher cutting speeds (450 ft.min^{-1}) formula (16) should be used for the calculation of the cost. As seen in Figure 6, the difference between the values calculated with the complete formula and the approximation are in this particular case small and rather negligible.

For practical uses it is not necessary to determine the cost by the complete formula, as the approximation will have the respective minimum at a higher cutting speed.

Shape of the Cost Curve.---Generally the minimum occurs always at a distinct cutting speed, but sometimes the shape of the cost curve is flat, so that the cutting speed can vary in a

AISI TS 8620, Tungsten Carbide, Hi-Jet

\$/piece

0.070

0.065

Exact Formula

Simplified
Formula

300

400

500

600

700

800

v

900

ft.min⁻¹

1000

Figure 6. Cost Curves Derived with Simplified and Full Formula

wide range without changing the cost too much. The slope of the curve depends on the cutting speed (responsible for the declining slope) and the exponent n of the tool life equation (increasing slope). The curve of the minimum is not so distinct with higher cutting speed, as is seen in Figures 7 and 8.

HSS tools, particularly when used with the conventional cooling and lubricating method of overhead flooding of the cutting oil, furnish a sharp bended curve. The use of Hi-Jet cooling and lubricating decreases the total cost for the same tool by some 14 per cent, and flattens the curve.

Machining the same materials with tungsten carbide tools brings for optimal conditions a gain of the minimum cutting cost of 28 and 33 per cent for overhead flooding and 13 and 17 per cent for Hi-Jet lubrication and cooling. The difference between the two cooling and lubricating systems is here smaller in the cost consideration ($< 2,5$ per cent), but the improvement lies in a considerable increase of the cutting speed of about 17 per cent. In other words, the productivity is increased by this amount, or the given order is finished in a respective shorter time.

Cutting Speed for Maximum Production.--The ratio between v_p and the economical cutting speed v_e increases with higher speeds. For high speed steel and therefore low cutting speed

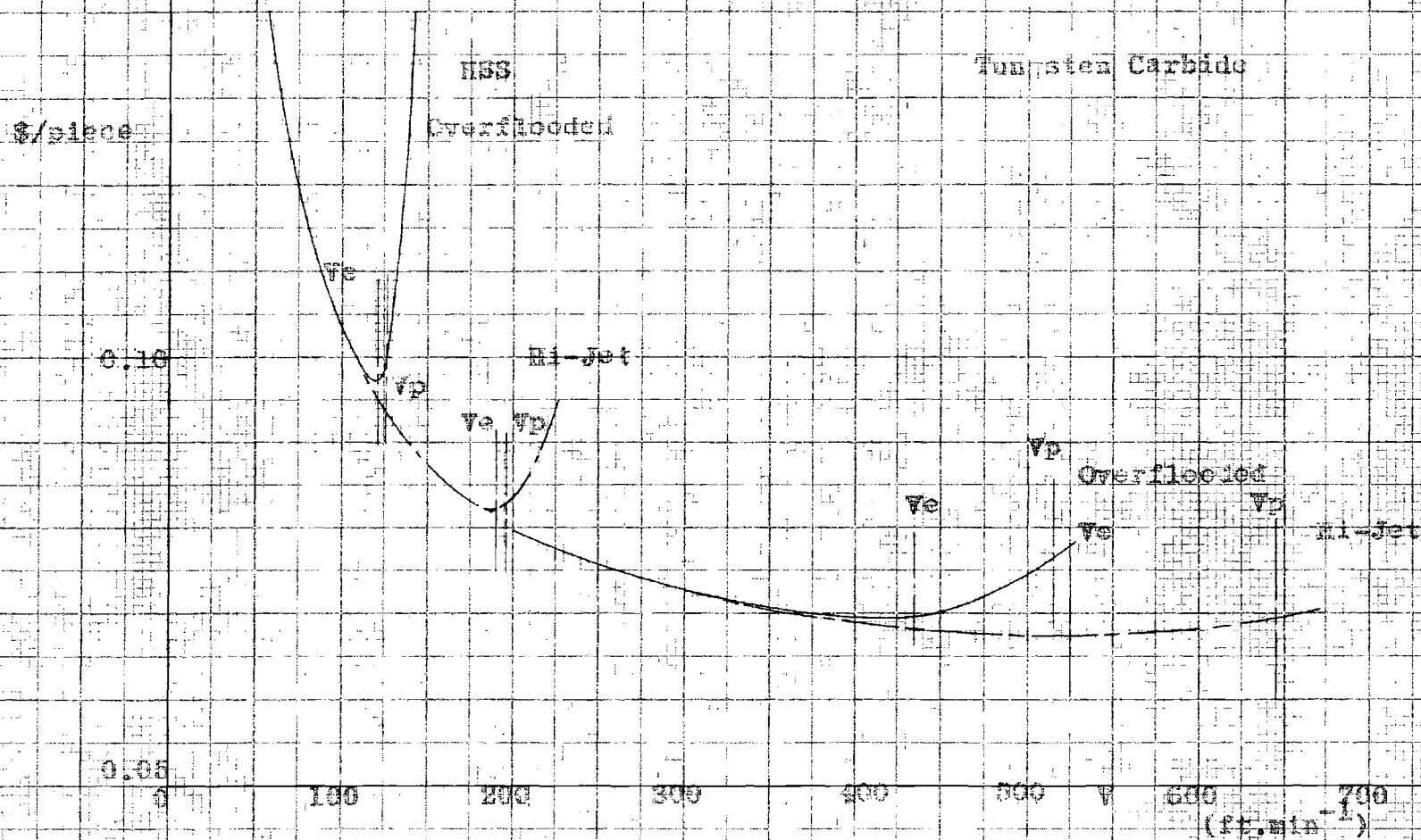


Figure 7. Machining Cost for Cutting SAE 1045

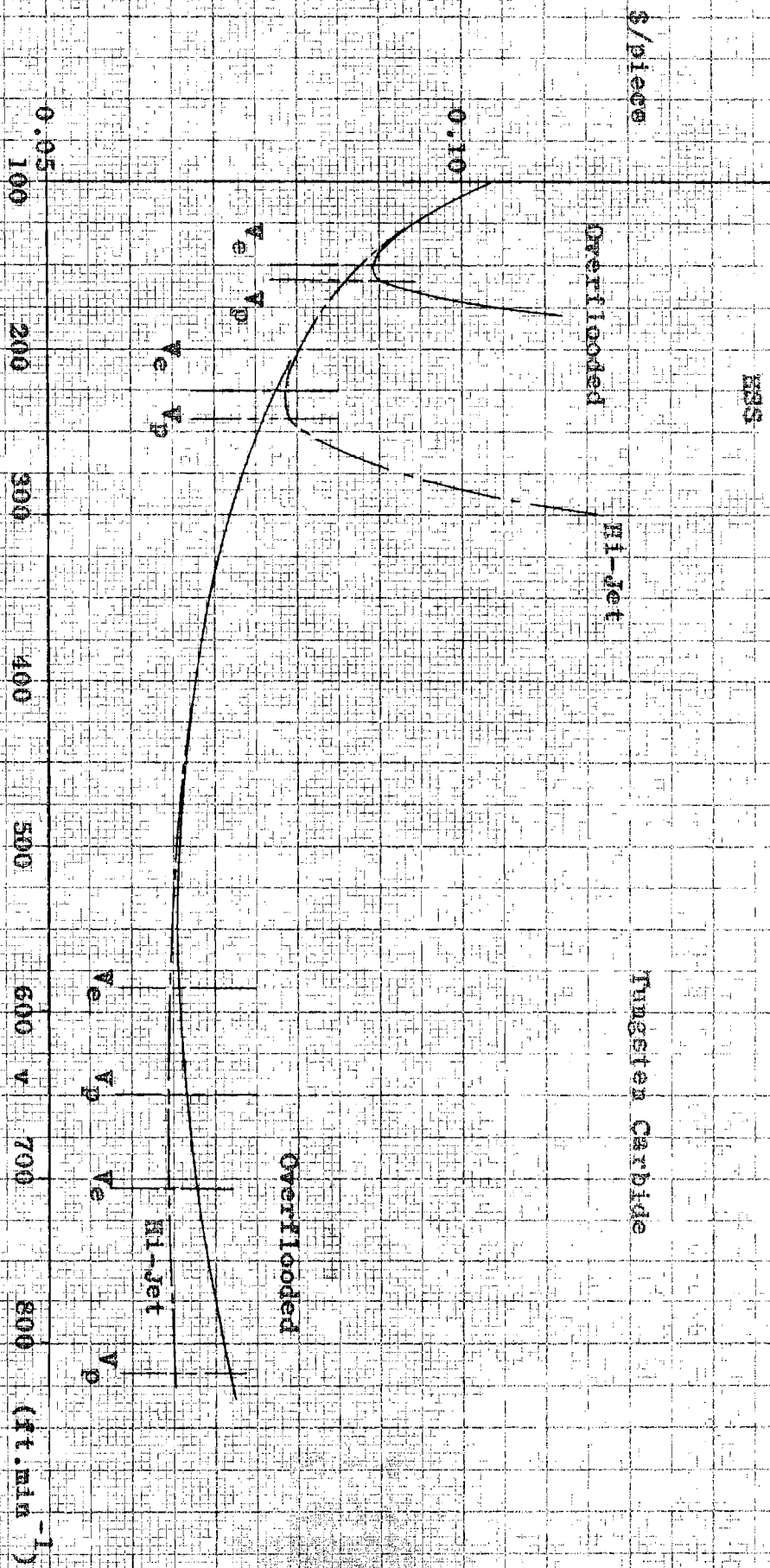


Figure 8. Machining Cost for Cutting AISI T3 8620

the two are nearly the same, and the respective costs are not much different. For carbide tools, the difference between the two cutting speeds is more than 100 ft.min^{-1} . The increase of the cost for machining SAE 1045 for maximum economical production is about 14 per cent. In the example for AISI TS 8620 (Fig. 8) there is practically no difference between the two costs.

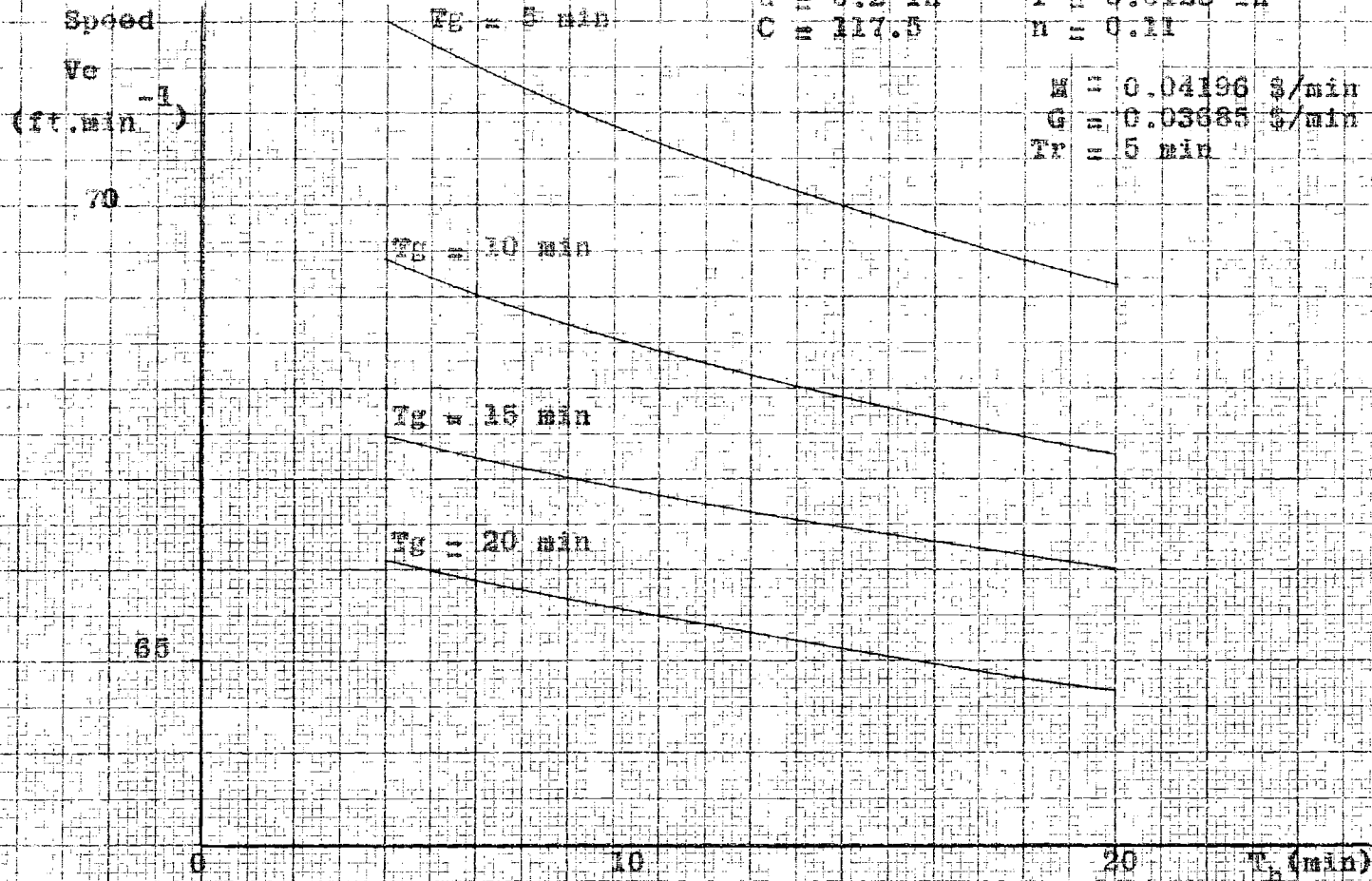
In conclusion, it is reasonable to run the machine by cutting with high speed steel at the speed of maximum production. By machining with carbide tools the cutting speed should be increased about half-way between the cutting speed for maximum and economical production without a large increase in the cost.

Condition for Minimum Cost.—Minimum cutting cost, as it is expressed in formula (19), is discussed in the example of machining SAE 3140 with HSS tool (Table 4).

$$v = \frac{C \cdot m^n}{\left[\left(\frac{1}{n} - 1 \right) (m \cdot T_R + G \cdot T_g + C_T + H) \right]^n} \quad (19)$$

In Figure 9 the time for handling the tool is varied, when the grinding time and the setting time are held constant. It is seen that the economical speed v_e decreases with increasing handling time as well as with increasing time for grinding. Because generally the decreasing economical cutting speed is equal to an increase of the production cost, the increasing handling time means higher cost.

Cutting SAE 3140 with
HSS 18-4-1, dry
 $d = 0.2$ in $f = 0.0125$ in
 $C = 117.5$ $n = 0.11$



$H = 0.04196$ \$/min
 $G = 0.03685$ \$/min
 $T_r = 5$ min

Figure 9. Condition for Minimum Cost: Handling Time Varied

70
 V_e
($f_{\text{min}} - 1$)

Cutting SAE 3140 with
HSS 12-4-1, dry
 $d = 0.2$ in. $f = 0.0125$ in
 $c = 117.5$ $m = 0.11$

$H = 0.04196$ \$/min
 $C = 0.03685$ \$/min
 $T_h = 2$ min

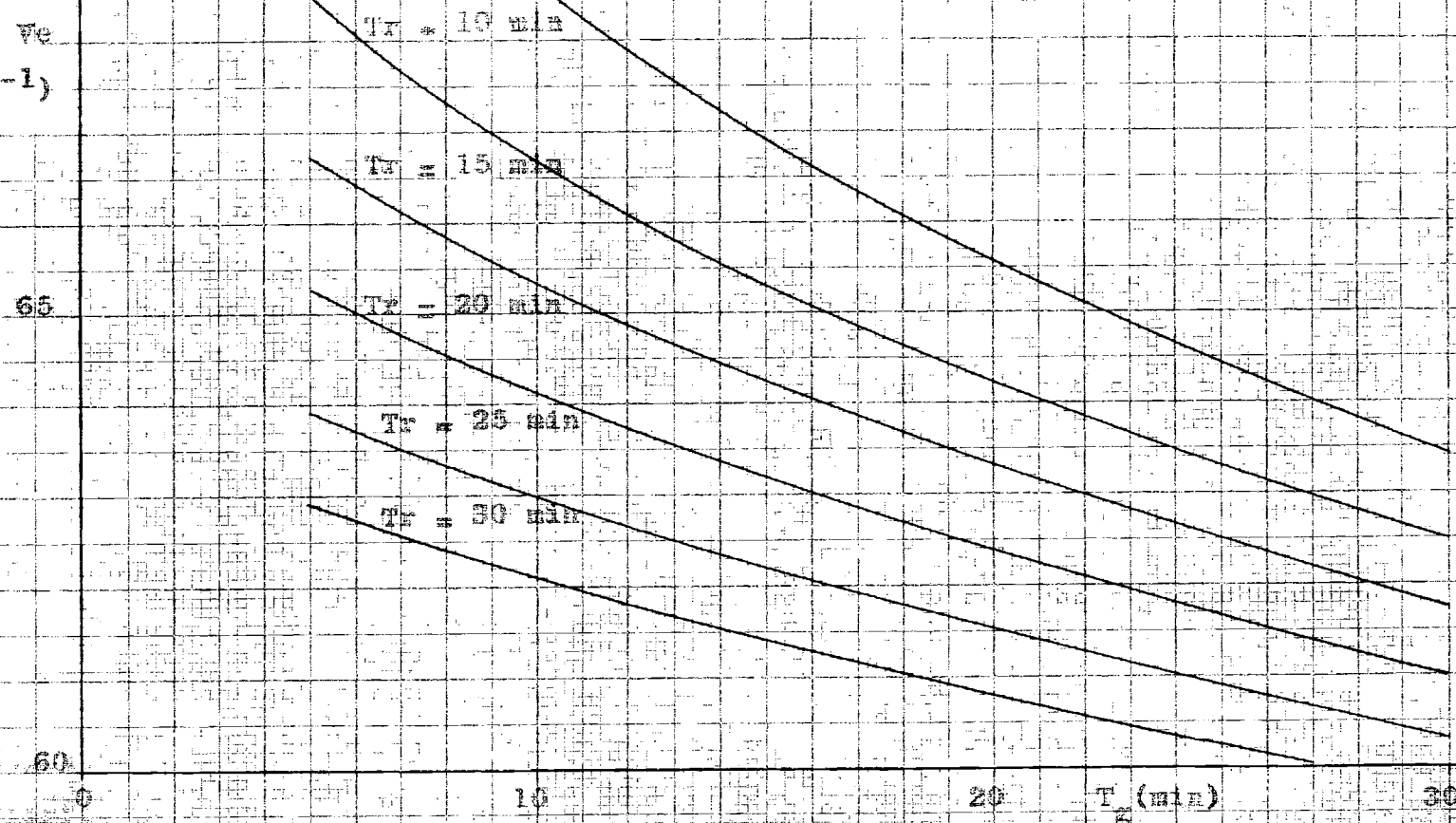


Figure 10. Condition for Minimum Cost; Resetting Time Varied

Figure 10 shows the condition for the economical cutting speed when the handling time of the tool per sharpening is held constant (8 min) and the resetting time is varied between five and twenty minutes. Here the cutting speed is the function of the time needed for regrinding the tool per sharpening. The curves have a similar shape to that of Figure 9, but the decrease of the v_e values is greater, according to the higher operation cost of grinding.

For comparison there is in this figure also the function of the cutting speed for maximum production plotted. These values are arrived at by using the formula (23). The distance between this curve and the curves for economical machining are a measure of how close the two speeds are. Naturally, for higher resetting time the two curves are closer, as also when the time required for grinding is shortened.

Figure 11 shows the condition for the economical cutting speed when the original cost of the machine is between \$5,000 and \$15,000. With higher machine cost the economical cutting speed shifts also to higher values. As functions of the resetting time, these curves are principally the same as shown in Figure 10. Also, the curve for maximum production is plotted here. It may be noted that this curve is independent of the value of the machine and it is only a function of the resetting time and the constants for machining C and n .

Cutting SAE 3140 with
 M33 18-4-1, dry
 $d = 0.2$ in $f = 0.0125$ in
 $C = 117.5$ $n = 0.11$

$T_D = 8$ min
 $T_H = 15$ min

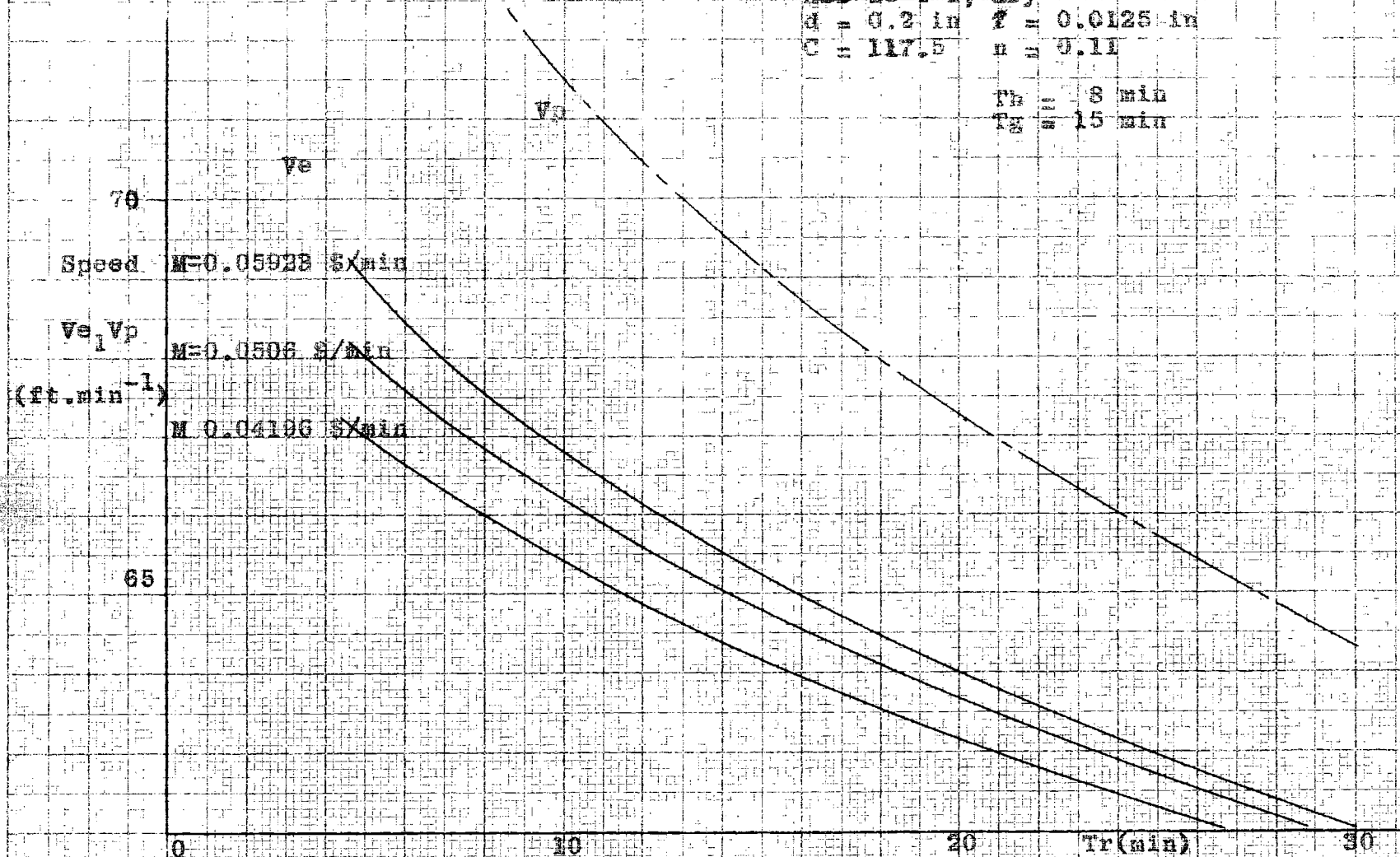


Figure 11. Condition for Minimum Cost: Initial Cost Varied

Cutting SAE 3140 with HSS 18-4-1 dry

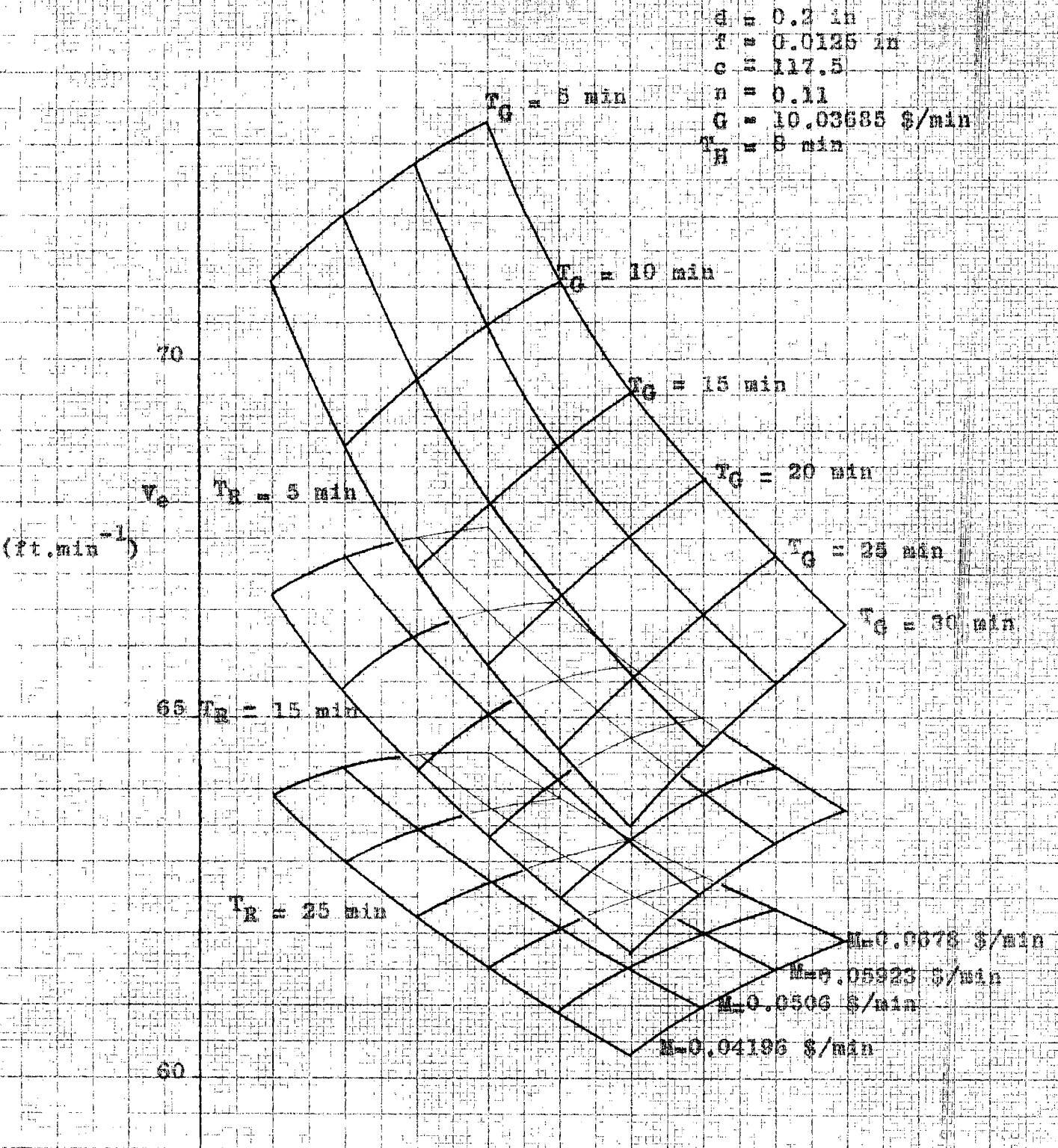


Figure 12. Economical Cutting Speeds

Finally, Figure 12 shows the whole set of economical cutting speeds v_c as a function of grinding, resetting time and the machine rate, when the time for handling the tools is set constant at 8 min. and the constants for machining $C = 117.5$ and $n = 0.11$. In this figure the dependability of the different factors is well demonstrated and it is possible to interpolate any desired values within the given range.

CHAPTER VI

CONCLUSION

Limitation of the Results.---The results of the preceding chapter are based upon the equation for tool life. Unfortunately, its constants C and n are known only in very few cases, because they are functions not only of the material and the tool, but also of the cutting conditions. Generally, with increased cutting depths both C and n decrease; with increasing feed, C decreases while n increases.

On the other hand, the tool life equation is only an approximation which does not always approach zero monotonically. Sometimes there may be one definite increase of tool life shown before the tool life curve declines to zero. In this part the curve is known as "valley of death", and its occurrence is connected with the two types of welds between tool face and the chip: the pressure weld for cutting temperature below recrystallization temperature of the softer material and the temperature weld, which occurs above the critical temperature.¹³ Therefore, increased cutting speed can furnish under certain conditions a far better tool life than could be expected.

Because tool life is affected much by the relation of the hardness at operating temperature of the two materials, it may be possible to increase the tool life by heating the

surface of the work piece before it is cut. This treatment does not only reduce the hardness of the material, but also eliminates the strain hardness normally incurred because of the previous cut.

The results obtained in this thesis are only for continuous cuts. Intermittent cuts will change the conditions, since in this case the tool is strained by shock or impact load. This calls for a tough tool material and only in a few cases are the properties of cemented carbides sufficient.

The examples of the previous chapter involved rather special materials. The reasons are first, other data were not available, and second, the principal considerations are the same for all materials.

Recommendations.---The use of carbides as cutting tools is highly recommended. It decreases not only the machining cost considerably, but at the same time it also increases the production rate. The use of carbides is only limited by the brittleness of the tool material. Proper support and avoiding of intermittent cuts will make possible their use in many additional operations, such as the work on a planer or shaper.

The cutting speeds for economical machining have to be held to close tolerances especially for HSS tools, or relatively small cutting speeds. For higher cutting speeds, as recommended for carbide tools, costs do not increase so rapidly when the speed is not properly chosen.

The machining cost for maximum production is, for cutting with high speed steel tools, only slightly larger than the cost for economical machining. But in machining with carbide tools the cost for maximum production is considerably increased. So it is recommended that, between the limits of the speed for economical production and the speed for maximum production, a cutting speed which provides a higher production rate but does not approach the cost for maximum production should be chosen.

The cutting speed for economical production decreases with increasing handling cost of the tool, tool cost, machine rate of grinding and grinding time as related to the sharpening of the tool. These costs should be minimized as much as possible.

Increasing machine cost requires a somewhat higher cutting speed for economical machining. This is true because the value of the increased production rate is greater than that of the time lost for resetting the tools.

The scope of this thesis was limited by the data available, but for future studies it would be recommended that all known results of experiments in the line of metal cutting be collected. With such a compilation it would be possible to present in tables the tool life equations for most of the common materials and tools. Another possible investigation would be the finding of the functions of the constants of the tool life equation for different cutting conditions.

While the results of this thesis primarily apply to mass production, they can also be employed with the same benefit to very small production.

TABLES

Table 1. Fixed Machine Rate for Different
Initial Machine Costs

Initial Cost	\$5,000.00	\$10,000.00	\$15,000.00	\$20,000.00
Depreciation & Interest over 20 yrs @6% \$/year	435.90	871.80	1,307.70	1,743.60
Tax & Insurance 2% \$/year	100.00	200.00	300.00	400.00
Total Fixed Machine Cost \$/year	\$ 535.90	\$ 1,071.80	\$ 1,607.70	\$ 2,143.60
Maintenance & Repair 10% \$/year	500.00	1,000.00	1,500.00	2,000.00
Total Yearly Costs \$/year	1,035.90	2,071.80	3,107.70	4,143.60
Cost per hour when 2000 machine hr/year assumed \$/hr	\$0.518	\$1.036	\$1.554	\$2.072
Labor including work- man compensation and insurance \$/hr	2.00	2.00	2.00	2.00
Total machine cost per hour \$/hr	\$2.518	\$3.036	\$3.554	\$4.072
Machine cost per min \$/min	\$0.04196	\$0.0506	\$0.05923	\$0.06786

$d \backslash f$	0.002	0.004	0.006	0.008	0.010	0.012
0.0312	5.43×10^{-8}	9.45×10^{-8}	1.3×10^{-7}	1.63×10^{-7}	1.97×10^{-7}	2.3×10^{-7}
0.0625	1.08×10^{-7}	1.51×10^{-7}	2.6×10^{-7}	3.36×10^{-7}	3.92×10^{-7}	4.58×10^{-7}
0.125	2.16×10^{-7}	3.78×10^{-7}	5.2×10^{-7}	6.51×10^{-7}	7.84×10^{-7}	9.17×10^{-7}
0.25	4.34×10^{-7}	7.56×10^{-7}	1.04×10^{-6}	1.32×10^{-6}	1.57×10^{-6}	1.83×10^{-6}
0.375	6.51×10^{-7}	1.14×10^{-6}	1.54×10^{-6}	1.97×10^{-6}	2.35×10^{-6}	2.73×10^{-6}
0.50	8.68×10^{-7}	1.52×10^{-6}	2.08×10^{-6}	2.64×10^{-6}	3.14×10^{-6}	3.65×10^{-6}

Table 2. k-Values (\$/ft) for Different Machine Rates
in Function of Feed f and Cutting Depth d

Table 3. Fixed Machine Rate for Sharpening
on Tool Grinder

Initial cost		\$ <u>1,500.00</u>
Depreciation & interest over 20 years @6%	\$/year	130.80
Tax & insurance 2%	\$/year	<u>30.00</u>
Total fixed machine cost	\$/year	160.80
Maintenance & repair 10%	\$/year	<u>150.00</u>
Total yearly cost	\$/year	<u>310.80</u>
Cost per hour when 2000 machine hours per year assumed	\$/hr	0.2054
Labor including workman compensation & insurance	\$/hr	2.00
Total machine cost	\$/hr	<u>2.2054</u>
Machine cost per min G	\$/min	<u>0.03685</u>

Table 4. Data for Condition of Minimum Cost

Machining SAE 3140 with HSS - Tool, dry

Depth d	0.2 in
Feed f	0.0125 in
Shape	8,22,6,6,6,15,3/64
C	117.5
n	0.11
T_c/s	0.000525 \$/s
G	0.03685 \$/min
H_c/s	0.0125 \$/min

Table 5. Data for Machining SAE 1045 and
AISI TS 8620

		Tools	
		High Speed Steel	Tungsten Carbide
Depth of cut d		0.100	0.100
Feed f		0.0105	0.0105
Shape		10,12,8,10,6,6,3/64	0,8,7(10),7(10),15,15,1/32
		with chip breaker	
Chemical composition		Mo,8%; Cr,4%; Va,1%; W1,5%	Tungsten carbide
a	1.0 in.ft	T _{c/s}	0.000525 HSS
Ti	0.5 min		0.024 \$/s carbide
To	600 min	G.T _G	0.553 \$/s
N _L	1000	H	0.1 \$/s
T _R	10 min	m	0.0506 \$/s

Constants of Equation for Tool-Life

Material	Lubricant	HSS		Carbide	
		n	C	n	C
SAE 1045	:Overhead				
	:flooding	0.0434	160	0.200	1075
	:Hi-Jet	0.0435	245	0.243	1490
AISI TS 8620:	:Overhead				
	:flooding	0.065	220	0.150	1240
	:Hi-Jet	0.081	356	0.169	1575

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